

HEARING THRESHOLDS

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1 INTRODUCTION

Thresholds of hearing define the lowest sound levels (absolute hearing thresholds) that a listener can detect as well as the highest (upper limits of audibility) sound levels that a listener can tolerate. These thresholds are used to describe hearing sensitivity and the dynamic range of hearing for both normal and hearing-impaired listeners. This chapter reviews the presentation and calibration procedures for sound field measurements and earphone measurements used to obtain absolute hearing thresholds to pure tones. Absolute thresholds obtained in a sound field are used to estimate minimal audible field (MAF) thresholds, while those absolute thresholds obtained when the sounds are presented over earphones are used to estimate minimum audible pressure (MAP) thresholds. The chapter compares the relationship between (absolute) MAF and MAP thresholds and provides a brief discussion of the psychophysical procedures used to obtain these thresholds. The chapter ends with a brief description of the thresholds of feeling and discomfort that described the upper limits of audibility and allows for the calculation of the dynamic range of hearing.

2 THRESHOLDS

Absolute hearing thresholds are the lowest sound pressure levels (SPLs) required for listeners to detect sound. The stimuli most frequently employed to obtain hearing thresholds and therefore to measure hearing sensitivity

are pure tones in the frequency range from 500 through 4000 Hz. Although complex stimuli such as frequency-modulated tones and narrow-band noises can also be used to measure hearing thresholds, this chapter will describe procedures for the use of pure tones. For audiological evaluations testing is usually performed with a pure-tone audiometer, an instrument for measuring hearing sensitivity that provides pure tones of selected frequencies at calibrated SPLs. The results of such testing are recorded on an audiogram, a graph showing hearing (threshold) level as a function of frequency. *Hearing (threshold) level* (HL) is the number of decibels that the listener's threshold of hearing lies above the zero reference level of the audiometer for that frequency. Thus, *0 dB HL (hearing level)* represents this zero reference level, which is based on the average hearing level of a large number of young adults considered to be otologically normal. The SPLs corresponding to 0 dB HL have standardized both nationally and internationally.^{1,2}

In most cases, the listener's ability to hear everyday sounds in normal rooms or outdoors is ultimately of primary interest, but that ability is difficult to test directly for obvious reasons. Measurements of the thresholds of hearing that employ pure tones allow for the easy and accurate reporting and interpretation of the status of an individual's hearing, frequency by frequency, in each ear. Two ways of presenting sounds are typically used: Sounds can be presented over loudspeakers with the listener in the sound field or over earphones fitted to the listener (earphones are the more frequent method used to obtain thresholds of hearing). For both ways of presenting sounds, the SPLs are calibrated so as to produce 0 dB HL thresholds for the average normal listener. It is, however, difficult to determine directly the ability, willingness, and response tendencies of the individual in the test situation. *Psychophysical procedures* prescribe

the methods of sound presentation and threshold calculation used to estimate thresholds. These psychophysical procedures help ensure that the obtained thresholds estimate the lowest SPL a listener can detect at each test frequency.

Given that hearing levels are referenced to “normal hearing,” any two thresholds determined on a given listener might be expected to agree, regardless of the method used to estimate the threshold or how the tones were presented to the listener. In practice, the accuracy and reliability (correctness and repeatability) of a given threshold depend on several factors:

1. Accuracy of calibration of the sound source, which is typically performed with the listener absent
2. Idiosyncratic effect of the individual listener’s ear (and head in the case of sound field testing) on the stimulus delivered to the listener’s eardrum by the sound source.
3. Accuracy of the zero reference SPL used for the calibration of the sound source
4. Level of background noise entering the listener’s ear canal
5. Listener’s willingness and ability to cooperate in the task of determining the level of sound for threshold
6. Method of stimulus presentation
7. Response procedure (type of psychophysical procedure)
8. Number of responses averaged to obtain a single threshold estimate

The eight factors listed above fall into two categories: (1) sound presentation and calibration and (2) threshold calculation method. The first yields an estimate of the SPL entering the auditory system under the measurement conditions, and the second yields an estimate of the lowest sound pressure level at which “hearing” occurs, the threshold. Discussions of “threshold” sometimes fail to make clear the distinction between *absolute hearing threshold*, measured in units of the minimum SPL required for audibility, and *relative hearing threshold level (HL)*, measured in units of the number of decibels above the average normal hearing threshold SPL at that frequency. Figure 1 summarizes the various thresholds discussed in this chapter: minimum-audibility thresholds (MAF and MAP thresholds) and thresholds for discomfort and feeling, which estimate the upper limits of audibility.

3 SOUND FIELD MEASUREMENTS

Minimum-audible-field thresholds are SPLs for pure tones at absolute threshold, measured in a free field at the position of the listener’s head but in the absence of the listener, using plane, progressive sound waves. The MAF thresholds are usually determined for listeners facing the source (0° incidence), listening with both ears (binaurally), at 1 m from the sound source, and are based on progressive plane-wave assumptions. If the loudspeaker is approximately 1 m from the measurement microphone [the standard method for calibrating microphones can be found in ANSI S1.10-1966(R1986)⁹], then the difference in diffraction around the head between a progressive plane wave and a progressive spherical wave will be negligible.

The acoustics of the room (reflections and standing waves) in which the measurements will be made can affect the sound as it travels from the loudspeaker to the listener. An anechoic room may reduce standing waves, especially at high frequencies, although most anechoic rooms do not eliminate reflections at very low frequencies (below 200 Hz). If other sound field conditions are used, they should be specified. For example, if thresholds are measured in a *diffuse sound field*, then they should be identified as *MAF (diffuse-field)* thresholds. In a diffuse sound field sound arrives at the listener from *all* angles (including above and below) with equal probability (see ISO/R226-1985²).

Under plane-wave conditions, the pressure at one ear depends on the angle of the sound source relative to the ear of the listener. The data in Fig. 2 show the MAF¹⁰ thresholds obtained for frequencies ranging from 300 to 15,000 Hz and at azimuth (horizontal plane) angles circling the head (0° represents the condition in which the speaker is directly in front of the listener). Binaural MAF thresholds obtained when both ears are used may be slightly lower (3 dB or less) than monaural MAF thresholds obtained when the listener uses his or her more sensitive ear. Thus, both the type of sound field and the monaural or binaural listening condition influence the threshold estimates when free-field MAF thresholds are obtained or reported.

To achieve a monaural listening condition, one ear of a listener must be covered with a hearing protector. The ANSI standards S3.19-1974(R1979)¹¹ and S12.6-1984(R1990)¹² specify the measurement methods for determining the attenuation characteristics of hearing protectors. A combination of an in-the-ear hearing protector and an over-the-ear protector may be used to achieve the greatest amount of attenuation. A masking noise can also be presented over an earphone to one ear in order to mask sounds arriving at that ear. The ANSI

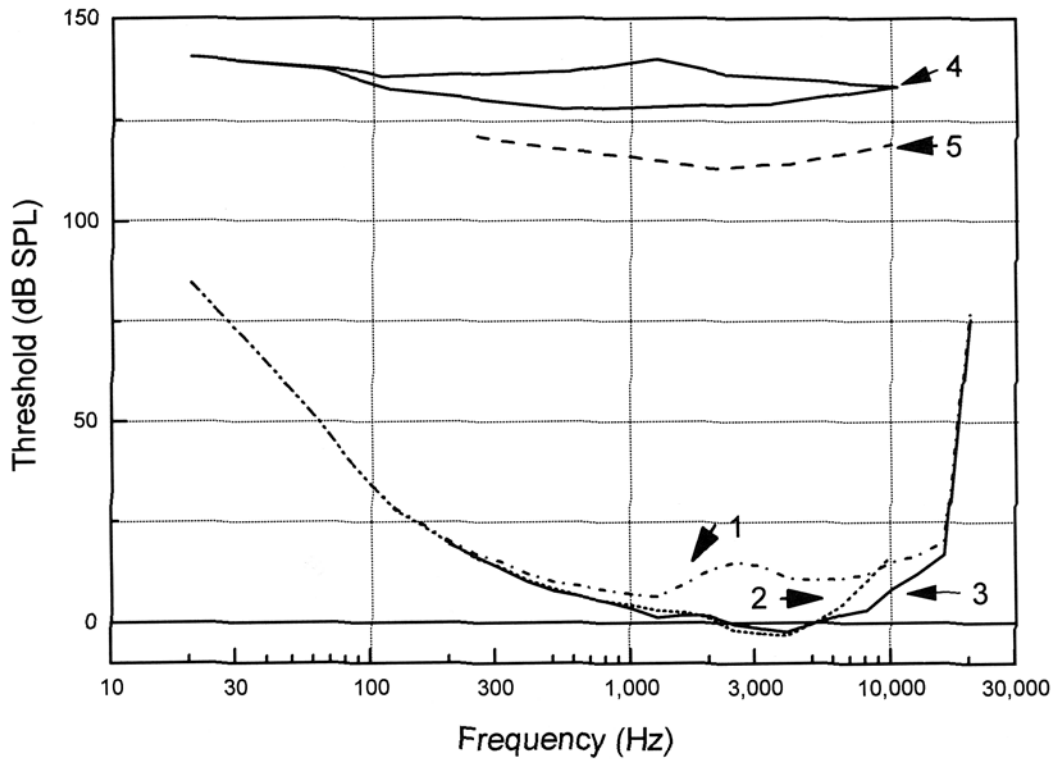


Fig. 1 Thresholds of hearing (minimum-audibility thresholds) expressed in decibels SPL shown as a function of the test frequency for three conditions: curve 1, binaural MAF thresholds,³ obtained for 0° azimuth; curve 2, monaural MAF thresholds³; curve 3, thresholds obtained in a diffuse sound field MAF(Diffuse Field). Curves 4 and 5 represent thresholds associated with the upper limits of audibility. The thresholds shown as curve 4 represents the range of thresholds when listeners report the level that led to a feeling of “tickle,” “pain,” or “feeling.”⁴⁻⁷ Thresholds of discomfort are shown as curve 5.⁶⁻⁸

standard S3.6-1989¹ describes the sound levels of noise that are effective for masking the sounds at one ear while allowing sounds to be detected at the other ear.

Because the angle of incidence of the sound is so important, small head movements can often cause large changes in the sound pressure presented to the eardrum in a MAF procedure. This is particularly true in the 6–8-kHz region for free-field sounds of 0° incidence (approximately plane wave), where a null-in-eardrum SPL of 20–30 dB can occur due to an antiresonance excited in the concha.¹³

The MAF thresholds from two conditions are shown in Fig. 1: (1) binaural MAF thresholds obtained for 0° azimuth and (2) binaural MAF (diffuse-field) thresholds. These curves were obtained by combining the data for MAF thresholds (discussed below) with data relating eardrum SPL with sound field and SPLs.^{3,14,15} Column 1 of Table 1 provides the International Standardization Organization (ISO) standardized MAF thresholds,² with low-frequency corrected values^{3,14} shown in col-

umn 2. Additional studies¹⁶ indicate that the ISO standard thresholds may underestimate 0-HL levels by 1–4 dB above 500–1000 Hz. On the other hand some recent studies tend to support the uncorrected ISO values at low frequencies.¹⁶

4 EARPHONE MEASUREMENTS

Although thresholds obtained from earphone presentations are often referred to as MAF thresholds, for the sake of clarity MAF thresholds will be restricted to the following definition,¹⁰ “the [sound] pressure amplitude at the observer’s eardrum.” The MAF curve in Fig. 1 is an estimate of the minimum audible sound pressure at the eardrum required for threshold.^{3,15}

Although the minimum audible pressure at the eardrum is independent of the type of (airborne) sound source,^{3,17} an audiometric earphone is normally not calibrated in terms of the eardrum pressure it produces but

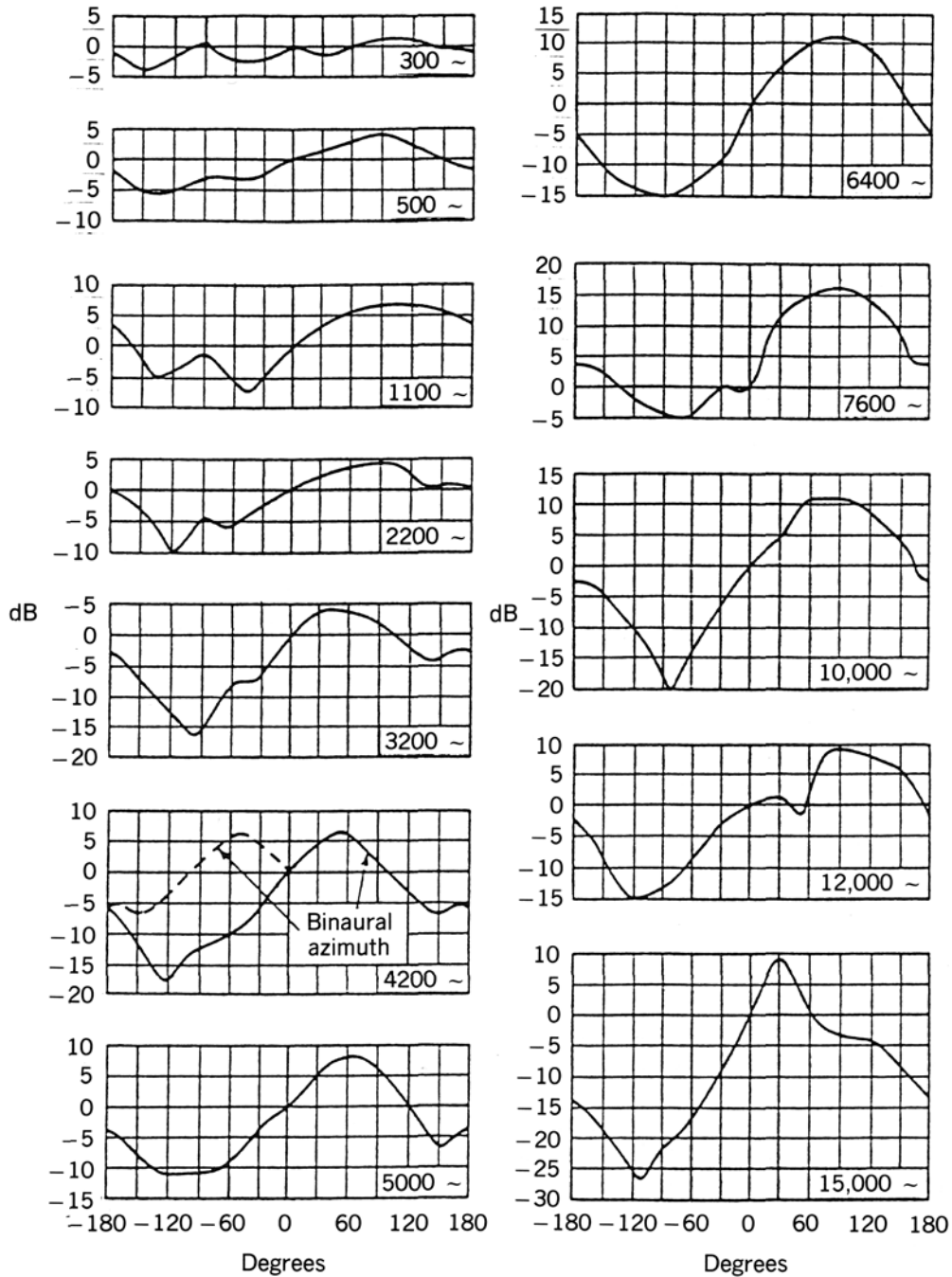


Fig. 2 Minimum audible field thresholds² for one ear are shown as a function of the azimuth angle between the listener and the loudspeaker (0° is directly in front of listener, 180° directly behind). Each panel represents a different test frequency. The MAF thresholds for each azimuth angle are referenced to that measured at 0°.

in terms of the *coupler* pressure it produces when the *average-normal-threshold volage* is applied to the earphone terminals. That is, at the eardrum, the SPL is estimated from the sound level in a test coupler attached to the earphone. Such couplers are typically designed to roughly approximate the average acoustic properties of

the ear of a normal hearing listeners. The zero reference SPLs for a particular earphone–coupler combination are called the *reference equivalent threshold sound pressure levels* (RETSPLs) and are given in the earphone calibration tables of audiometry standards, such as shown in Table 2. Table 2 shows the RETSPLs¹ given in ANSI

TABLE 1 Minimum Audible Field Thresholds

Frequency (Hz)	MAF Thresholds (dB SPL)	Corrected
100	25.1	33
125	20.7	30
160	16.8	24
200	13.8	18.5
250	11.2	17
315	8.9	12
400	7.2	8
500	6.0	
630	5.0	
800	4.4	
1000	4.2	
1250	3.7	
1600	2.6	
2000	1.0	
2500	-1.2	
3150	-3.6	
4000	-3.9	
5000	-1.1	
6300	6.6	
8000	15.3	
10000	16.4	
12500	11.6	

Note: Minimum audible field (MAF) thresholds are expressed in decibels SPL as specified in the International Standardization Organization's acoustic standard ISO/R226-1985 (Ref. 2). The conditions that must exist for these thresholds to apply are (1) the source is at 0° azimuth (frontal incident), (2) the sound field is a progressive plane wave, (3) listening is binaural, and (4) the listeners are otologically normal people in the age from 18 to 30 years inclusive. Corrected values are shown for certain low frequencies (from Ref. 3).

S3.6-1984. Note that each earphone-coupler combination generates a different set of values for RETSPL, only one of which is equal to the estimate of MAP (column 5). That earphone-coupler combination, the Zwislocki coupler occluded-ear simulator (described in more detail below), is designed to provide the best simulation of the average ear and eardrum.

4.1 Supra-aural Earphones

Supra-aural earphones are calibrated in a simple "6-cc" coupler such as the NBS-9A coupler [ANSI 3.7-1973(R1986)¹⁸ specifies the dimensions for this coupler]. The coupler has a volume of 6 cc, an approximation to the average volume of the normal human outer ear between the earcap of the earphone and the eardrum. During calibration, the earcap of the earphone rests on the upper edge of the coupler and is held in place by a force of between 400g and 500g. A calibrated microphone⁹ measures the SPL.

The NBS-9A coupler only roughly simulates the acoustic impedance of the average male outer ear cov-

ered with a supra-aural earphone. Based on the real-ear, probe-microphone data,¹³ the actual eardrum pressure may range between 1 and 9 dB greater than the coupler pressure over the frequency range of approximately 1000-3000 Hz.¹ At frequencies below 400 Hz, on the other hand, the actual eardrum pressure produced by a supra-aural earphone will usually be substantially less than the measured coupler pressure due to leakage of sound from around the earphone fitted to the ear. Thus, care must be used in fitting the earphone to the outer ear. A headband with a spring to hold the earphone cushion against the ear should be used. Jewelry, eye-glasses, and hair from the head should not lie between the earphone cushion and the ear. The earphone must be fitted with a proper cushion (see ANSI S3.6-1989¹) to help ensure a good fit to the ear. When measurements from both ears are to be made, both earphones are calibrated and the differences between earphones is kept as small as possible (the two phones should differ by less than 2.5 dB for each frequency tested).

Supra-aural earphone thresholds obtained at frequencies above 8000 Hz may also vary considerably (10 dB or more) from listener to listener due to standing waves within the outer ear. That is, because the length and volume of the outer ear are of approximately the same size as the quarter wavelength of these high-frequency tones, standing waves may be produced that lead to nonuniform distribution of sound pressure within the outer ear. A number of techniques have been used to obtain MAP thresholds above 8000 Hz and to calibrate the expected sound pressure within the outer ear. However, none of these techniques has been standardized and large differences in RETSPL values (on the order of 30 dB) exist among the thresholds obtained across studies.²⁰

The ambient background noise level at the location of the listener must be no higher than the values described in ANSI S3.1-1977(R1991).²¹ Background noise is likely to be especially deleterious for estimating thresholds below 1000 Hz using supra-aural earphones. Thus, supra-aural earphone thresholds should be measured in a sound-proof room meeting the acoustical requirements of ANSI 3.1-1977(R1991).²¹ In addition to ambient background noise, thresholds obtained with supra-aural earphones at low frequencies (500 Hz and below) are often affected by physiological noise in the outer ear. This noise is caused by the sound of blood circulating in the arteries and veins of the head and neck and by sounds associated with respiration and body movements.

4.2 Insert Earphones

Insert earphones sealed directly into the ear canal with deeply inserted foam eartips of the type used for hearing protection (but including a sound tube through the

TABLE 2 Reference Equivalent Threshold Sound Pressure Level (RETSPL) Thresholds for Different Earphone-Coupler Combinations

Frequency (Hz)	RETSPL Thresholds (dB SPL)					
	Western Electric 705A ^a (1)	Telephonics TDH 39, 39P ^a (2)	Telephonics TDH 49, 49P; TDH 50, 50P ^a (3)	Telex 147A ^a (4)	Insert ^b (5)	Etymotic ER 3A ^c (6)
125	45.5	45	47.5	47	30	27.5
250	24.5	25.5	26.5	27.5	19	15.5
500	11	11.5	13.5	13	12	8.5
750	7.5	8	8.5	8.5		
1000	6.5	7	7.5	6.5	9	3.5
1500	6.5	6.5	7.5	5		
2000	8.5	9	11	8	15	6.5
3000	7.5	10	9.5	7.5	15.5	5.5
4000	9	9.5	10.5	9	13	1.5
6000	8	15.5	13.5	17.5	13	-1.5
8000	9.5	13	13	17.5	14	-4.0

^aSupra-aural earphone.

^bInsert, occluded ear simulator.

^cInsert, HA-1 coupler.

Note: From ANSI, S3.6-1989 (Ref. 1); columns 1-4 are from Table 6, column 5 from Table G.1, and column 6 from Table G.2. The listeners are otologically normal, the supra-aural earphones have been fitted with the proper cushion (described in Ref. 1), and the earphones have been calibrated via an acoustic coupler meeting the requirements of ANSI S3.7-1973(R1986) (Ref. 18) or 3.25-1979 (R1986) (Ref. 19).

center of the eartip) reduce the problem of the probable masking effect of physiological noise in the outer ear that occurs when supra-aural earphones are used. Such a deeply sealed eartip can also provide substantially more attenuation of ambient noise than that provided by supra-aural earphones and cushions.²² Insert earphones are usually better at controlling leakage and acoustic cross-talk between the phones at each ear than are supra-aural earphones.²²

Calibration of insert earphones is performed with the same couplers used to acoustically calibrate hearing aids, using either a *2-cc coupler* like the HA-1 coupler or an *occluded-ear simulator* such as the Zwislocki coupler (see ANSI S3.25-1989¹⁹). The 2-cc coupler was designed to fit over a standard 1-in. (2.54-cm) microphone and to have dimensions that minimize troublesome standing waves at high frequencies. The 2-cc coupler roughly approximates the volume of air between the tip of an insert earphone and the eardrum, and it provides the equivalent volume of normal eardrum compliance at low frequencies. An *occluded-ear simulator* provides a closer approximation than the 2-cc coupler to the acoustic impedance of the average adult occluded-ear canal and eardrum. In addition, the occluded-ear simulator provides an approximation to the standing-wave field that exists in the average adult outer ear. Because the insert earphone presents a high-impedance source to

the ear, a constant-decibel relationship exists at any frequency between the SPL in a 2-cc coupler and that in an occluded-ear simulator. Thus, either calibration may be used with equivalent results.²³ The 2-cc coupler RETSPL values for the ER-3A insert earphone have been standardized, and these calibration values are given in column 6 of Table 2.

5 RELATIONSHIP BETWEEN (ABSOLUTE) MAF AND MAP THRESHOLDS

5.1 Stimulus Conditions

In all procedures absolute thresholds are expressed as decibels of sound pressure level (dB SPL): x dB SPL = $20 \log_{10}(y/20 \mu\text{Pa})$, where y is the pressure of the test signal measured in units of micropascals. The referent value of $20 \mu\text{Pa}$ is approximately the SPL required for the average young adult to just detect a tone with test frequencies in the range of 1000–3000 Hz.

For most measurements the tonal signals used to obtain thresholds are pulsed sinusoids of a single frequency (within $\pm 3\%$ of the nominal frequency), produced with low total harmonic distortion (usually less than 3%), having a duration of at least 400 ms, and turned on and off with rise-decay times of at least 20 ms in order

to reduce audible clicks and to further restrict spectral energy to the region of the tonal frequency. The frequencies of the tones are usually within the range of 20–20,000 Hz and are often 125 Hz and the six higher octaves of 125 Hz. Absolute thresholds remain approximately constant for durations longer than 300 ms. The exact relationship between thresholds and signal duration is frequency dependent.²⁴ Absolute thresholds are also known to increase with the age of the listener, and women often have slightly lower thresholds than men, especially for an older population.²⁵ There is also evidence that for test frequencies above 2000 Hz the right ear of many listeners is slightly more sensitive than the left ear.²⁵ In addition, the otologic condition of the listener will obviously affect the threshold estimated from a hearing-impaired listener.

5.2 MAF Thresholds Are Lower Than MAP Thresholds

The MAF and MAP thresholds do not agree when they are actually measured (see Fig. 1). For instance, head diffraction and external-ear resonances combine to cause

some 15–20 dB increase in eardrum pressure over that in a frontally incident sound field at 2700 Hz. Since the sound field pressure is calibrated with the listener absent, this increase causes an exactly comparable decrease in sound field pressure required for threshold, that is, in the MAF data. The MAF thresholds are thus always lower than MAP thresholds by an amount that reflects the gain of the external ear at each frequency plus the binaural advantage (of 3 dB or less) when binaural MAF is compared to monaural MAP.

By examining the difference between the MAF and MAP thresholds, one might conclude that a “missing 6 dB^{3,17}” existed between sound field (MAF) and earphone (MAP) thresholds, even when both had been converted to sound pressure at the eardrum (see the difference between curves 1 and 2 in Fig. 1). As Fig. 3 indicates, there are experimental difficulties that lead to that erroneous conclusion.¹⁷ Figure 3 (solid curve) shows the MAP threshold estimate given in ANSI S3.6-1989,¹ based on independent estimates of MAP from free-field MAF data corrected for head diffraction and external-ear resonances and from earphone RETSPL data corrected for real ear-coupler differences.³ Given the

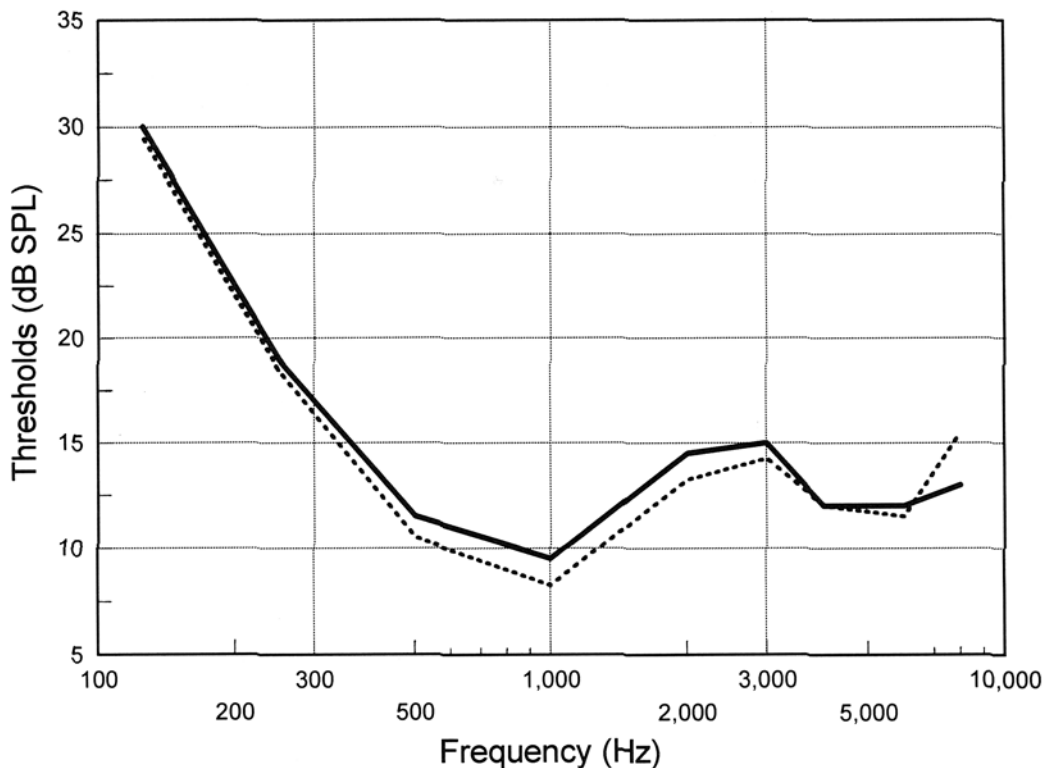


Fig. 3 Minimum audible pressure, RETSPL in decibels SPL as a function of test frequency. The solid curve shows corrected MAP thresholds from ANSI 3.6-1989,¹⁰ and the dashed curve represents thresholds obtained with the ER-3A insert earphone converted to the equivalent occluded-ear simulator (Zwislocki-coupler) pressures.³ The small difference between these two curves suggests there is no missing 6 dB.³

fixed relationship between 2-cc coupler sound pressure and occluded-ear coupler sound pressure at each frequency and the good agreement between sound pressure measured in real ears and in the occluded-ear coupler,²³ a relatively direct estimate of MAP can be made from insert earphone thresholds. Figure 3 (dashed curve) also shows MAP at the eardrum averaged from four studies in which 2-cc coupler RETSPL data for the ER-3A insert earphone were reported and subsequently converted to equivalent occluded-ear coupler pressure.³ Thus, the MAP estimate shown as a solid curve in Fig. 3 was based on MAF and supra-aural earphone RETSPL data, while the dashed curve in Fig. 3 was based on insert earphone RETSPL data. The greatest difference between the two curves is 2.5 dB, indicating that the difference zero reference SPLs required for calibrating different sound sources are essentially the same. Any differences that are measured reflect only differences in the calibration procedure.³ That is, there is no missing 6 dB.

The shape of the MAP and MAF absolute threshold functions are approximately the same, showing a loss of sensitivity below approximately 1000 Hz and above approximately 4000 Hz. The loss of sensitivity at low frequencies below 1000 Hz declines at approximately 6 dB/octave and at approximately 24 dB/octave above 4000 Hz (the ability to estimate the slope of the high-frequency side of the thresholds of hearing function is much poorer than estimating the low-frequency slope due to the difficulty in measuring thresholds above 8000 Hz, as discussed previously). A threshold of 0 dB SPL represents a pressure of 20 μ Pa, an extremely small pressure. By making some assumptions about the acoustic energy present in the Brownian motion of air molecules, it can be shown that a sound presented at 0 dB SPL is only 20–30 dB more intense than that being produced by Brownian motion.²⁶ A number of factors governing the acoustic transfer function of the outer and middle ears have been suggested as explanations for the shape of the thresholds of hearing functions.²⁷

The data shown in Fig. 1 are based on test frequencies that are widely spaced. When thresholds of hearing are measured over a small range with test frequencies close together, the thresholds vary from test frequency to test frequency in a pattern that is unique to the individual being tested. This *microstructure* to the audiogram can show threshold changes of 5–10 dB that occur when the test frequency has changed by just a few hertz.^{28,29}

6 PSYCHOPHYSICAL PROCEDURES

A number of psychophysical procedures and variations of these procedures have been used to obtain MAF or MAP thresholds. In general, sounds are presented to listeners at different SPLs, and listeners make judgments

concerning the presence or absence of the sound. Each psychophysical procedure specifies a precise method for presenting the tones and obtaining a threshold from the functional relationship between the listener's responses and the SPLs presented to the listeners. Hearing thresholds obtained using different psychophysical procedures for the same sound stimulus may differ by 5 dB or more.³⁰

Thresholds obtained from the various psychophysical procedures often depend both on the integrity of the auditory system and on other variables that affect how a listener responds. The variables that are not associated with auditory processing but may influence a listener's response are referred to as *response bias variables*.³⁰ For instance, the instructions given to a listener may make the listener liberal or conservative in the use of the response alternatives. Since thresholds depend on how the listener responds, response bias variables may affect the obtained threshold. *Forced-choice methods* are often the preferred method for reducing the effect of response bias variables on the obtained thresholds. In some forced-choice methods the tonal signal is presented half the time and no tonal signal is presented half the time, and the listener is to indicate whether the tonal signal or no tonal signal was presented.³⁰ Other methods that yield thresholds that may depend on response bias but are often used because of their efficiency include the *method of limits* and the *method of adjustment*. In the method of limits, the tester decreases and then increases the level of the test stimulus and on each presentation asks the listener if he or she detected the test tone. In the *method of adjustment* procedure the listener adjusts the level of the test tone until it is just barely detectable.

Quite often one requires an efficient procedure that yields similar thresholds when the same listener is tested more than once. The typical clinical threshold procedure uses a method of adjustment, which takes approximately 45 s per threshold and yields a standard deviation for a single threshold estimate of about 3.5 dB.³¹ Several studies³¹ suggests that versions of automatic adjustment procedures, such as the Bekesy procedure, provide a more efficient procedure: on the order of 30 s per threshold with a standard deviation for a single threshold estimate of approximately 2 dB. The forced-choice procedures often produce the lowest thresholds and are intrinsically free of response bias, but they are the least efficient procedure, requiring on the order of 3 min per threshold estimate with a 3-dB standard deviation.³¹

7 THRESHOLDS OF FEELING AND DISCOMFORT

Thresholds of feeling and discomfort are used to estimate the highest SPLs that the human ear can tolerate and are used to define the *upper limits of audibility*. Thresh-

olds estimating the upper limit of audibility are often obtained by increasing the sound level of intense sounds until listeners report that they have experienced certain sensations or perceptions that indicate the auditory system may be jeopardized. In most procedures the SPL of the tone at each frequency is adjusted upward, in a type of method of limits procedure, until the listener indicates that the sound level has caused the required sensation. The sound level is not increased any further to prevent risk to the auditory system, and this final sound level forms an estimate of the upper limit of audibility for that run, and the procedure is repeated again. The average final sound level for a number of runs (usually four or more) forms a threshold for any one frequency. The same stimulus conditions that were recommended for MAP and MAF threshold measurements are usually used for estimating the upper limit of audibility, and special care is required to ensure that the tones are not distorted by the sound presentation apparatus at these high levels.

A number of sensations indicate that the sound level has reached the upper limit that the ear can tolerate. A listener can experience a "tickle," "prickling," "feeling," or "pain" sensation.⁴⁻⁷ Any of these sensations can be used as the response definition estimating the upper limit of audibility. However, asking listeners to indicate when they "feel" the sound in the ear is the most common criterion, and the other sensations and thresholds appear to be highly correlated with the sensation of feeling and the threshold of feeling.⁶ Curves 4 at the top of Fig. 1 display the sound levels that lead to thresholds of feeling, pain, and tickle. Considerable variability is to be expected when obtaining thresholds estimating the upper limit of audibility due to listeners' uncertainties in making determinations (response bias) of pain, feeling, tickle, and so on.⁶

Because of the risk of permanently damaging the auditory system, *thresholds of discomfort* (those SPLs leading to a report of "discomfort") are often used to estimate the upper limits of audibility. For many purposes, (e.g., the fitting of hearing aids), the definition of discomfort may include a context for the listening situation. For instance, the listener may be asked to indicate when the sound level has reached the point where he or she would no longer wear a hearing aid because the sound level was uncomfortable. The same procedure used for determining the thresholds of feeling is usually used to obtain the thresholds of discomfort. Curve 5 in Fig. 1 indicates the thresholds of discomfort.^{5,7,8} Thresholds of discomfort are less variable than, and 10–30 dB below, the thresholds of feeling⁵

The decibel difference between thresholds representing the upper limits of audibility and the thresholds of hearing define the *dynamic range of hearing*, which may be as large as 140 dB for frequencies between 1000 and

3000 Hz. The frequency range over which thresholds and estimates of the upper limits of audibility can be measured determine the *frequency range of audibility*, which ranges from 20 to 20,000 Hz for most young, otologically normal listeners. For most situations and listeners (e.g., for a hearing-impaired listener) changes in the dynamic range in any frequency region are due to changes in the thresholds of hearing.

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